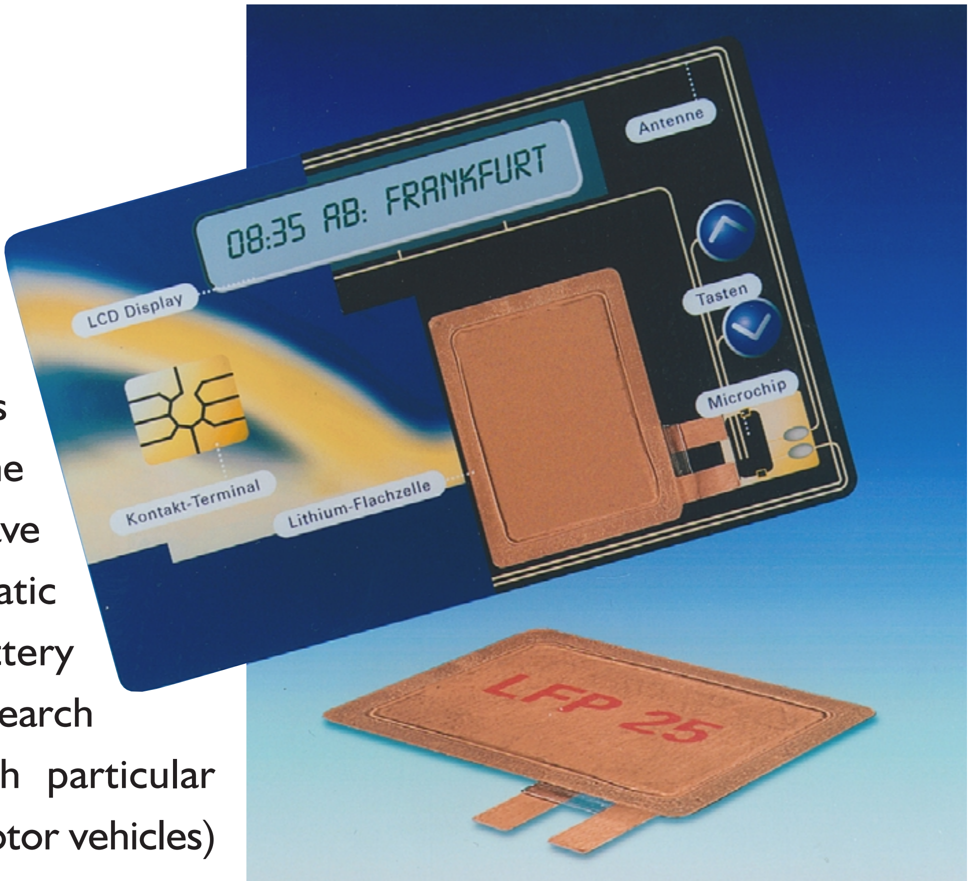
Battery technology today …

…and tomorrow

By E. Krempelsauer



Since the introduction onto the world markets of the Li-ion battery in the early/mid 1990s, there have been no dramatic developments in battery technology, although research on the fuel cell (with particular emphasis on its use in motor vehicles) has been the centre of attention during the past few years. Other interesting future developments are concerned with the proposal to alter the power source in motor vehicles to 42 V, the introduction of the lithium-polymer battery for mobile radios and telephones, and the demise of the nickel-cadmium (NiCd) battery.

Secondary lithium-ion (Li-ion) batteries were introduced commercially in the early 1990s (Ref. 1). A detailed report on their properties, applications, and suitable chargers may be found in Ref. 4. Since then, their use has increased greatly, particularly in laptop and palmtop computers and camcorders. World production grew from 140 million in 1996 to 385 million in 1999. This kind of growth, however, is not experienced in the mobile telephone markets.

Since its introduction, the technology has not changed other than in minute detail. The anode is usually made from graphite or manganese, and the cathode from a lithium-cobalt oxide or lithium-manganese oxide compound. The electrolyte is invariably an organic liquid containing lithium sulphate.

The highest energy density and longest life are provided by a graphite/ lithium-cobalt oxide combination, which is, therefore, the most frequently encountered. The battery capacity is somewhat smaller when a lithium-manganese oxide cathode is used, but this type of battery is slightly cheaper and offers environmental advantages, which makes a greater use in the future a certainty.

Batteries with a lithium-nickel oxide cathode have properties somewhere between those using lithium-cobalt oxide and lithium-manganese cathodes.

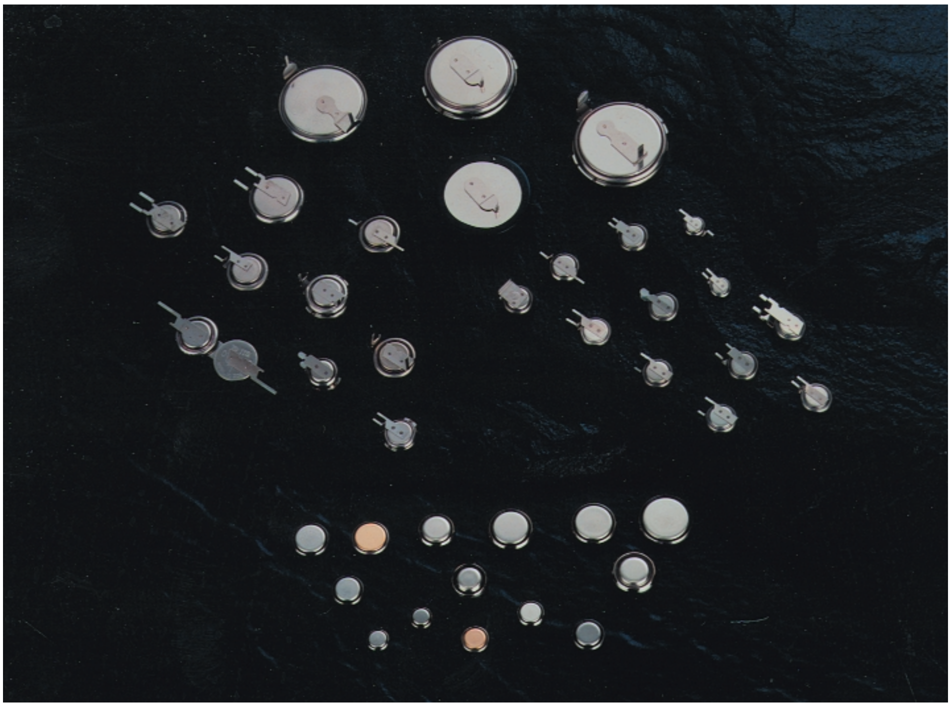


Figure 1. Rechargeable Li-ion button cells have a bright future in the memory/buffer battery market. Some of their advantages are low self-discharge and an e.m.f. of 3.6 V.

Small is beautiful

In the past few years physically very small secondary Li-ion batteries have come on the market. Their construction is normally button-shaped as shown in **Figure 1**. These batteries find application especially in computers. No fewer than 120 million of them are produced annually for use in real-time clocks alone. Compared with previously used nickel-cadmium (NiCd) and current nickel metal hydride (NiMH) button cells, Li-ion batteries have several important advantages, such as a significantly longer useful life (owing to the much smaller self-discharge) and the fact that a single 3.6–3.8 V Li-ion button cell can replace three NiCd or NiMH button cells (1.2 V each). Another important aspect is that when the cathode is made from manganese oxide the battery is much more environmentally friendly than batteries that use nickel, cobalt, or cadmium.

In an amazingly short time, Li-ion batteries have also found application in small electrically powered or hybrid road vehicles. Peugeot, for instance, have available their ‘Vedelic’ 106 which, powered by Li-ion bat-

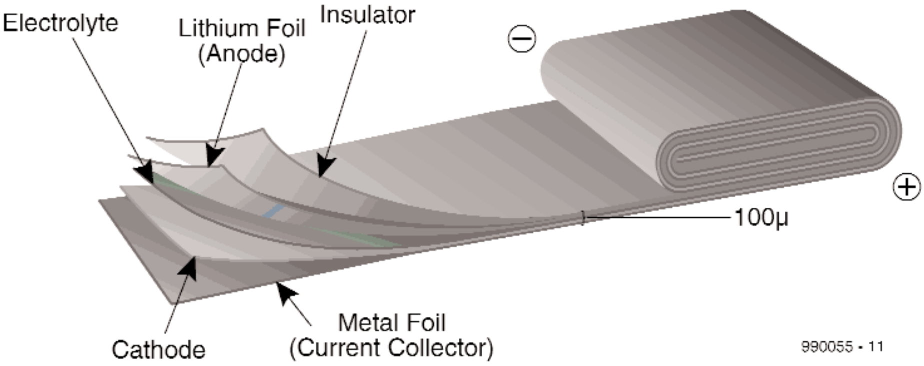


Figure 2. Basic construction of a lithium-polymer battery. When a single film of polymer is used, a battery can be formed that is thin enough to be integrated in a chip card.

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* Lithium, a rare element, is a soft, silvery metal that reacts with oxygen and water at room temperature; at higher temperatures, it also reacts with nitrogen and hydrogen.
Polymer is a substance having large molecules consisting of repeated units (monomers). There are a number of natural polymers, but synthetic polymers are used extensively in plastics.

teries from SAFT, has a range of 120 miles between charges and a top speed of 65 MPH.

The latest type of lithium battery, the lithium-polymer battery, is showing good results in experimental road vehicles. Producers such as 3-M-Hydro-Quebec have high hopes for a bright future of these batteries.

Lithium-polymer*

Research has been going for a number of years to produce a solid polymer electrolyte for lithium cells and batteries. The currently used micro-porous polymer film between anode and cathode serves merely as a separator. A solid polymer electrolyte would be able to serve both as electrolyte and separator.

The problem in pure polymer electrolyte lies in the low conductivity of lithium ions at room temperature (which limits the permissible loading of the cell): only at temperatures exceeding 100 °C does the conductivity become a practical proposition.

Current lithium-polymer batteries use a polymer electrolyte in which it is not the polymer but a liquid electrolyte that provides the ion conduction. In these batteries, the electrolyte is totally contained in the polymer film which therefore appears to have the mechanical properties of a plastic film.

If the anode and cathode were also constructed as thin films, it would be possible to manufacture thin, flat cells which could be made into a variety of shapes of battery—see **Figure 2**.

The aim of current research is to increase the energy output of the cell by the use of metallic lithium for making the anode. Once this is possible, and the anode is used in combination with a pure polymer electrolyte, an electronic protection layer becomes superfluous, which improves the possible energy density. Commercial production of 0.5–0.7 mm thick secondary lithium-polymer cells is already possible.

Lithium-polymer batteries currently used in mobile telephones are 3–7 mm thick and have capacities varying from 450 to 700 mAh. A typical model has a capacity of 500 mAh, an e.m.f. of 3.7 V, weighs 15 grammes, and measures only 50×33×4 mm. Apart from their higher energy density and improved reliability (leak-proof; short-circuit proof thanks to the polymer), they offer much greater flexibility in their construction. For

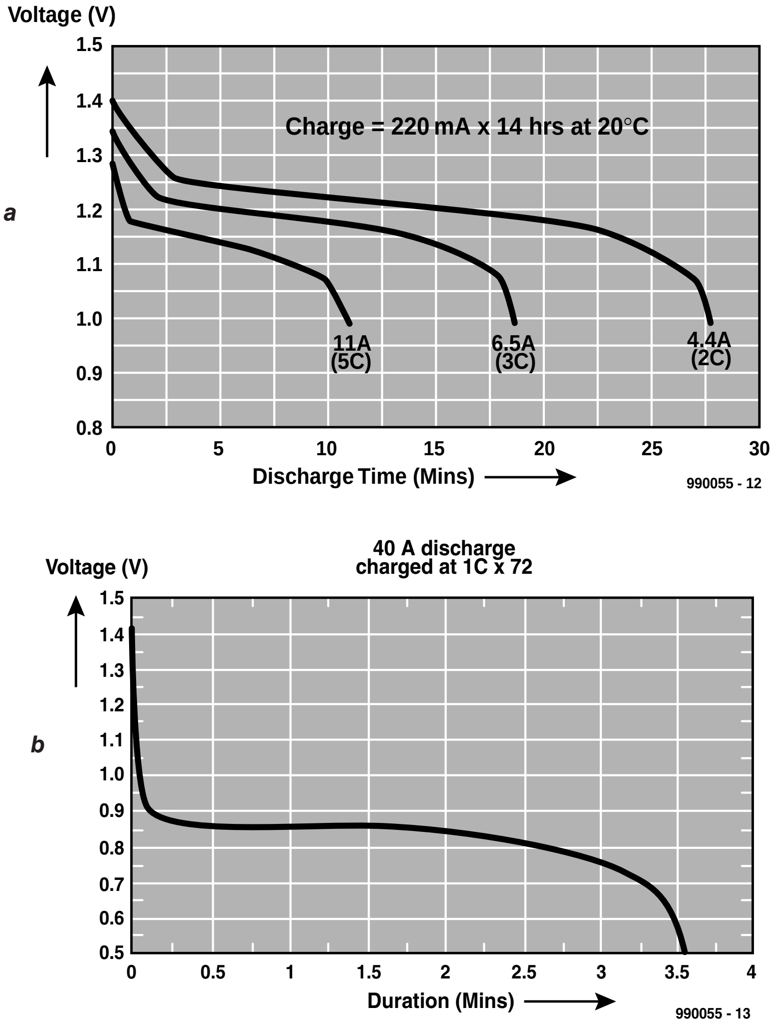

Figure 3. Discharge curves of a sub-C size NiMH battery at high output currents (a) and at a virtually short-circuit current of 40 A (b).

Figure 4. The 600 mAh NiCd battery in certain mobile telephones can readily be replaced by an 1100 mAh NiMH battery.

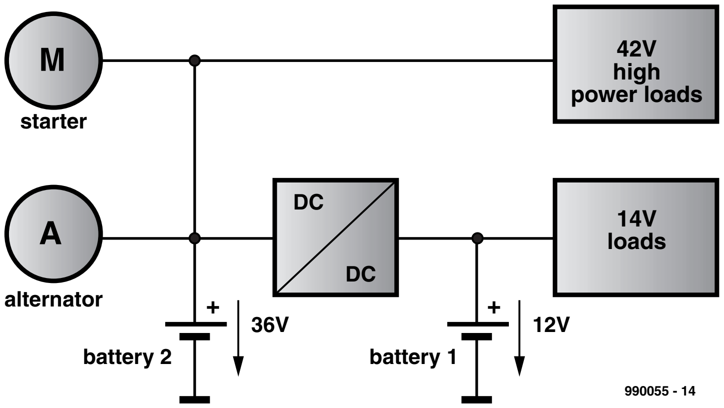

Figure 5. Future private motor cars may have 36 V batteries. The onboard supply may then be 14 V and 42 V.

instance, they may be integrated in equipment, such as the back of the display in a notebook computer.

Another application of thin-film lithium-polymer batteries (but only primary ones) is as current source for smartcards.

The end of nickel-cadmium

Within the electronics industry it has been known for some time, but it is not generally realized, that the days of the nickel-cadmium (NiCd) battery are numbered. A European Directive prohibits the use of NiCd batteries from 2008. This does not affect the European or American battery industries much since most of these batteries are manufactured in Asia.

However, the demise of the NiCd battery is not so much caused by environmental considerations as by the fact that they are largely being superseded by nickel-metal-hydride (NiMH) batteries, not only in emergency power supplies, but also in radio telephones, portable electric drills and other tools, model constructions, and others.

The widely used round sub-C NiMH battery (23 mm dia; 42.6 mm overall length) allows peak currents of up to 40 A to be drawn, and has a typical capacity of 3 Ah (see **Figure 3**). However, research aimed at increasing the capacity continues unabated. Until recently AA size batteries had a capacity of 1200–1300 mAh, but this has grown to 1500–1600 mAh, and is expected to reach 1800 mAh within a year. In other words, all things being equal, NiMH batteries have roughly double the capacity of a NiCd battery. Moreover, the differences between rechargeable NiMH and primary alkaline batteries for use in small to medium current applications are becoming smaller and smaller. At higher currents, the life per charge of NiMH batteries is greater than the overall life of primary alkaline batteries.

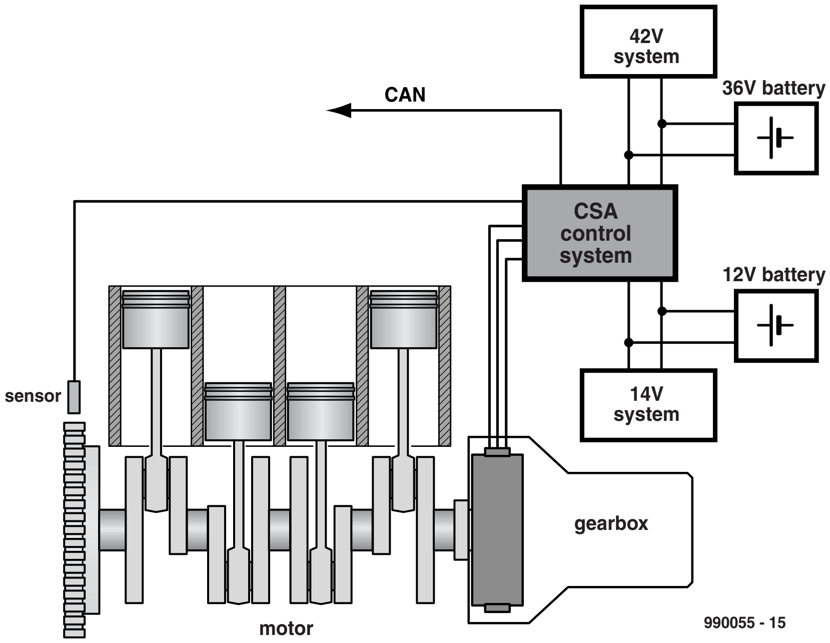

Figure 6. Future motor vehicles may have a Combined Starter-motor/Alternator (CSA) as shown here diagrammatically in a dual-voltage onboard supply system.

It should be noted, however, that there is a price to be paid for the high nominal capacity of high-power NiMH batteries in the form of a smaller life per charge and a less robust construction. For that reason, lower-capacity, more robust NiMH batteries should be used in applications where standby charging and frequent deep discharge are encountered, as in mobile telephones. For instance, the AA size NiMH battery specially developed by Varta for replacing the NiCd battery in certain mobile telephones has a capacity of only 1100 mAh. See **Figure 4**.

The rapid growth in capacity and the steadily falling price of NiMH batteries is the reason that Li-ion batteries have (as yet) made little inroad into the GSM market. There are even special voltage converter ICs available that enable a 3.6 V lithium cell in a mobile telephone to be replaced by two 2.4 V NiMH cells.

The development of high-current NiMH batteries makes these batteries suitable for use in hybrid-drive road vehicles. For instance, a 250 V, 10 A model produced by Varta lasted more than 30,000 miles without any problems. Varta has also developed an NiMH battery for the long-distance, electrically driven racing car 'Panoz Q9' that weighs only 100 kg (220 lb), yet delivers 90 kW of electrical power.

Fuel cells

Today, most of the industries that have a stake in vehicle engineering and production (oil industries, car makers) are far more interested in the fuel cell than in the NiMH or lithium battery. Ford, for instance, believe that fuel cells are the only basis for the clean propulsion systems of the future. DaimlerChrysler and several of their competitors plan to launch commercial fuel-cell powered cars in America and Europe by 2004-2005. This is, no doubt, in response to a Californian decree that by 2004 a tenth of all cars sold in the state must not produce any emission whatever. The European Union, too, is committed to drastically reduce harmful emissions from road vehicles. Iceland has pledged to become the world's first hydrogen-powered economy.

The simplest fuel-cell is one in which hydrogen is combined with oxygen from the air to generate electric power: the only by-products are water and heat.

A supply of gaseous hydrogen is fed to a compartment containing a porous sintered nickel cathode, while a supply of oxygen is fed to another compartment containing a porous sintered nickel anode. The electrodes are separated by a third compartment containing a hot alkaline electrolyte.

The electrodes are porous to enable the hydrogen and oxygen to react with the electrolyte: the nickel in the electrodes acts as a catalyst. At the cathode, the hydrogen reacts with ions in the electrolyte to form water, with the release of two electrons per hydrogen molecule:

$$H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$$

At the anode, the oxygen reacts with the water, taking up electrons with the aid of a platinum catalyst to form hydroxide ions:

$$\tfrac{1}{2}O_2 + H_2O + 2e^- \rightarrow 2OH^-$$

The electrons flow from the cathode to the anode through an external circuit as an electric current.

Although it is generally agreed that the fuel cell is *the* power source of the future, not everyone agrees what fuel it will use. Clearly, there is unlikely to be a market for hydrogen for some time. Initially, it seems likely that methanol or petrol will be used in cars, and natural gas or propane for power generation.

There are a number of constructions possible, but currently the most likely is the proton-exchange fuel cell. This is a sandwich of a cathode and an anode separated by a polymer membrane (containing the electrolyte).

An experimental small fuel cell developed by Germany's Fraunhofer Institute for Solar Energy Systems for powering a laptop computer rated at 25 W has a storage tank holding 130 litres of hydrogen. The fuel-cell proper and the hydrogen store are together about the same size as the original laptop battery. However, where the original battery had a cycle life of 2–3 hours, the fuel cell gives 10 hours of operation without the need for replenishing. This means that the fuel cell has a higher energy density than current Li-ion batteries while having a better life per charge.

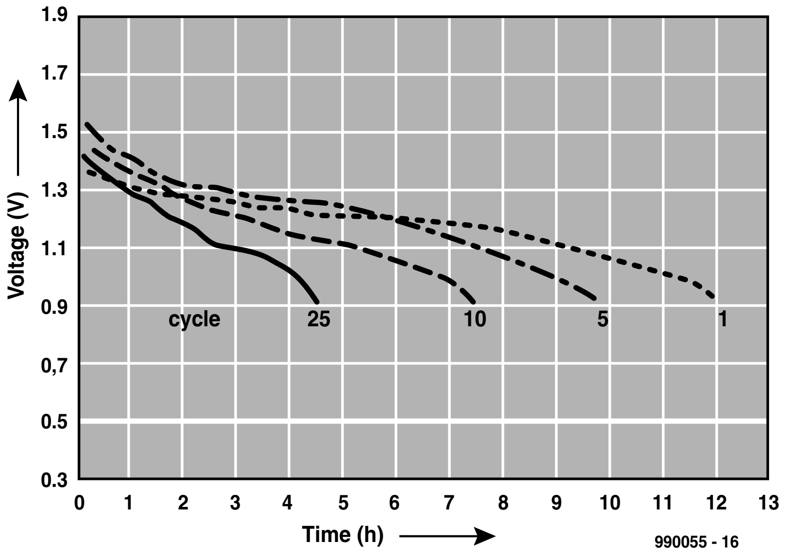

Figure 7. Voltage characteristics of an alkaline manganese secondary battery at a discharge current of 125 mA and up to 25 charge/discharge cycles.

42 V vehicles

After the Second World War, the battery voltage of private motor vehicles was standardized at 12 V (commercial vehicles 24 V, while motorcycles remained at 6 V for many years thereafter). Almost twenty years later, a start was made with equipping cars with an a.c. alternator instead of a d.c. dynamo. Today, it is planned to raise the battery voltage in private motor cars from 12 V to 36 V. This will probably be accompanied by the introduction of the combined starter motor/alternator (CSA) now in the development stages.

As far as the onboard power supply is concerned, this will probably be changed from 12 V to 42 V. It is almost certain, however, that there will be two supplies onboard: 14 V for the car electronics and other equipment requiring a low-voltage supply, and 42 V for units requiring higher powers (see **Figure 5**). There are very good reasons for a dual system, the most important of which are the increased power require-

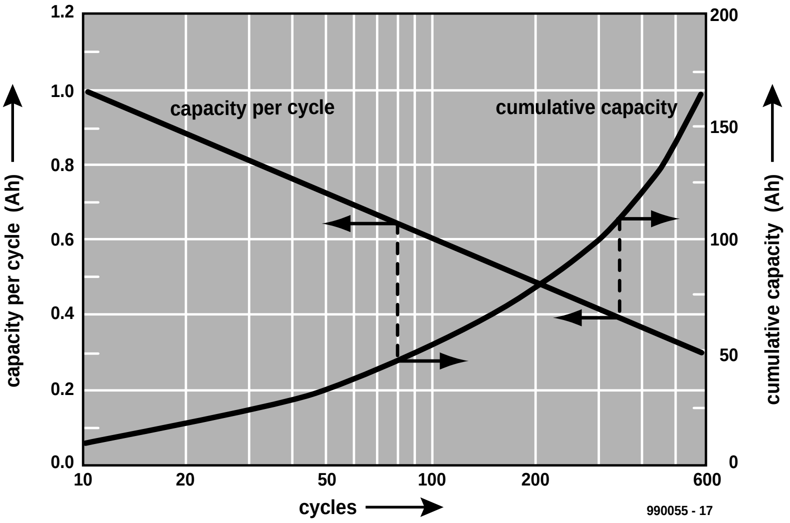

Figure 8. Correlation of depth of discharge, number of charge/discharge cycles, and cumulative capacity of an AA size alkaline manganese secondary battery. At a discharge current giving a capacity of 1000 mAh, the battery has a life of only 10 charge/discharge cycles.

ments owing to the greater use of electrical and electronic equipment; improvement of the efficiency of the electrical system; and a reduction in weight.

A higher voltage improves the efficiency, while a dual voltage system using two batteries enables the optimization of the different applications. It is likely that the 36 V battery, but almost certainly the 12 V battery, will be lead-acid versions of the so-called Absorbent Glass Mat (AGM) type. In this, an absorbent separator between the plates immobilizes the electrolyte. This construction makes the battery eminently suitable for use in cyclic or float applications, insensitive to orientation. The 36 V battery may also be a NiMH or Li-ion model.

The dual voltage concept, in conjunction with the combined starter motor/alternator, is an interesting and forward-looking means of saving energy and reducing weight.

The CSA, a compact 3-phase asynchronous machine that functions as starter motor and alternator, is fitted between the engine and the gearbox—see **Figure 6**. Electronic circuits assume all control and regulation functions, including rectification of the alternator output (rated at 68 kVA), alternator control, charging control of both batteries, and a 3 kW bidirectional 42/14 V DC/DC converter.

When the unit functions as alternator, it has an efficiency of more than 90% in the power range up to 4.2 kW. Used as starter motor, it can provide power bursts of more than 20 kW.

Optionally, when the vehicle is in motion, the CSA may be controlled to compensate any irregularities in engine output and to dampen any vibrations of the drive shaft. Provided the battery rating is adequate, the CSA may also aid the engine during stopping and acceleration manoeuvres. In this sense, it may be seen as an early part of a hybrid drive system.

Alkaline batteries, primary and secondary

A new generation of alkaline manganese primary batteries with higher capacity and permitting much improved high current operation has recently come onto the market. These batteries, available from all the usual manufacturers, are clearly better than their predecessors, particularly as far as their life at high-current output is concerned. For instance, when a current of 1 A is drawn from an AA size, the battery life is 1.5 hours (compared with one hour from earlier models). At a current of 600 mA, battery life is greater than 2 hours; at 150 mA, 14 hours, and at 120 mA, more than 18 hours.

This improved performance is due to a number of factors, such as a much reduced internal resistance. This is achieved by using fine, highly conductive graphite as an additive to the manganese dioxide cathode and highly refined, high-surface-area zinc powder for the anode. The new design gives a high-current density per unit volume, low internal resistance and impedance, and a relatively constant capacity over a range of current drawing and discharge schedules.

Alkaline manganese secondary batteries, in contrast to the latest NiMH batteries, cannot offer such high output currents. The 1.5 V e.m.f. quoted by most manufacturers drops fairly rapidly to 1.2 V when the battery is loaded. The internal resistance is quite high, so that the capacity at high output currents drops rapidly. For instance, the nominal capacity of a rechargeable AA size model rated at 1800 mAh is attained only if the output current is ≤ 30 mA; at 125 mA, it drops to 1500 mAh, and at 300 mA to 1200 mAh (all figures apply to a discharge down to 0.9 V).

The quoted capacities apply only to the first discharge of the battery; they are further reduced in proportion to the number of charge/discharge cycles—see **Figure 7**. These curves apply to a discharge current of 125 mA. The cycle-life of the battery can be improved only by not discharging the battery to a voltage as low as 0.9 V. When the battery is discharged below 0.9 V, its cycle-life is reduced significantly.

An important advantage over an NiMH battery is the much lower self-discharge. However, its greater environmental friendliness is arguable. Although a single alkaline manganese secondary battery has the advantage over a single NiMH battery, the NiMH comes out much better when energy consumption is considered. This is because of the following.

An alkaline manganese secondary battery (AA size) has a cumulative capacity of about 75 Ah when it is discharged at only 0.5 Ah per charge/discharge cycle. However, a NiMH battery has a cumulative capacity of at least 500 Ah, and normally 700 Ah. This means that in practical use a single NiMH battery is equivalent to 8–10 alkaline manganese secondary batteries or 100–500 alkaline manganese primary batteries. It is clear which is the more environmentally friendly battery.

[990055-1]

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